

ON ALIEN NOISE CANCELLATION FOR DOWNSTREAM DSL RECEIVERS

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**DEPARTMENT OF ELECTRICAL ENGINEERING
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by

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CERTIFICATE

This is to certify that the thesis titled **On Alien Noise Cancellation for Downstream DSL Receivers**, submitted by **Mr. Ramanjit Singh Ahuja**, to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy**, is a bona fide record of the research work done by him under our supervision. The thesis has reached the standards fulfilling the requirements of the regulations relating to the award of the degree.

The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

Digital Subscriber Lines (DSL) are an important part of the broadband communications infrastructure. With the advent of multi-user MIMO based DSL systems (called Vectored DSL), far-end crosstalk has ceased to be the dominant impairment in DSL receivers. Instead, alien noise sources (possibly intermittent in nature) such as power supplies, home appliances, motors, commercial radio broadcasts, and other services in the DSL band like PLC modems have become the primary impairments. While techniques like interleaved Reed-Solomon coding based forward error correction (FEC) and physical layer retransmission, incorporated into DSL standards can help mitigate the impact of these alien noise noises, additional partial or complete noise cancellation can complement the FEC and retransmission capabilities. Since DSL relies on differential mode (DM) transmission for the data signal over copper twisted pairs, and alien noise couples onto the twisted pair electromagnetically as a common mode (CM) signal, an additional CM sensor at the receiver offers an extra degree of freedom, which can be used to cancel the alien noise that leaks into the differential mode. However, there are two main challenges when using the CM sensor for noise cancellation. The first problem is that although the common mode to differential mode coupling can be modelled as a linear time-invariant (LTI) system, it has to be assumed as a finite impulse response (FIR) filter with a long impulse response (of the order of hundreds of taps), and no simpler model or detailed characterization is available. This results in high complexity for training and cancellation, as well as longer training time. The second challenge is that the estimation of the coupling (i.e., training of the noise canceller) has to be done in the presence of a much stronger data mode signal (around 25 – 30 dB stronger) than the alien noise signal in DM, which makes this problem akin to a signal of interest buried in impairment type estimation problem. Therefore, a

large amount of averaging is needed for accurate estimation, resulting in a slow convergence of the training algorithm. Decision-directed estimation cannot be directly employed, since the DM signal to uncanceled alien noise ratio can be lower by around 25 – 30 dB, as compared to the regular data mode signal to noise ratio (usually around 50 dB), resulting in error probabilities close to 1. This thesis aims to solve these challenges, in order to construct a practically feasible method for utilizing the common-mode sensor for alien noise cancellation, as well as explore additional issues introduced by considering the proposed method(s).

Our proposed solution is based on the use of the frequency-domain “Per-Tone” model for training and cancellation, wherein we falsely assume that alien noise has a cyclic structure, thus introducing an approximation in the CM-DM signal coupling model. The use of the frequency domain Per-Tone model allows us to introduce decision-directed estimation very conveniently since DSL uses OFDM data transmission. The Per-Tone model also enables low-complexity training and cancellation, besides having other implementation related advantages. We have proposed a low complexity two-stage algorithm for training the Per-Tone canceller with a non-decision-directed first stage, and a second iterative decision-directed stage, that has a reasonably fast convergence. We have provided a detailed analysis of the convergence of both stages of the proposed algorithm. The validation of the efficacy of the proposed algorithm presents an additional challenge, since there is no standard statistical noise model available for alien interference, as its nature varies widely from source to source. To work around this problem, we have demonstrated the efficacy of the algorithm via simulations using an adversarial non-stationary noise model.

Further, we have also proposed a joint time and frequency domain algorithm for training the noise canceller, which has high complexity but very fast convergence and provided some limited justification for its convergence. Additionally, we have also proposed another variant of the frequency-domain Per-Tone training algorithm, which has high memory requirements but faster convergence than the two-stage Per-Tone algorithm mentioned earlier. Both of these algorithms are not amenable to rigorous analysis but can be useful in practice.

The other significant contribution in the thesis is the analytical treatment of the Per-Tone model. The Per-Tone model, which falsely assumes that the alien noise signal has circulant structure, has an inherent approximation. Due to this inherent approximation, the residual post-cancellation noise in Per-Tone cancellation can be higher than the residual noise in cancellation by linear (time-domain) convolution. We have analytically derived the expression for the residual noise power and suggested a method to optimize it using a “post-training” delay adjustment. Next, we derive the exact relation between the “true” time-domain impulse response of the coupling and the response obtained by the inverse discrete Fourier transform of the Per-Tone coefficients. Using results from the asymptotic equivalence between Toeplitz and circulant matrices, we show that this exact relation can be approximated very simply in most practical cases, resulting in a simple method to derive the time-domain impulse response from the Per-Tone coefficients, which in turn can be used to offer improved cancellation performance. This line of analysis is further used to derive the analytical justification for the good performance of the Per-Tone model, despite its inherent approximation. We point out that in case of Per-Tone cancellation, the residual noise can be potentially strongly complex non-circularly distributed resulting in some additional loss of performance. We analyze this effect and show that for wide-band noise scenarios, this effect may be mild. Further, we analyze the impact of complex non-circularly distributed Gaussian noise on the performance of the four-dimensional (4D) Trellis Coded Modulation (TCM) used in DSL standards, and suggest measures to improve the performance of the code in this scenario.

सार

डिजिटल सब्सक्राइबर लाइन्स (DSL) ब्रॉडबैंड संचार का एक महत्वपूर्ण हिस्सा हैं भूमिकारूप व्यवस्था। बहु-उपयोगकर्ता MIMO आधारित डीएसएल सिस्टम (वेक्टरड डीएसएल कहा जाता है) के आगमन के साथ, दूर-अंत क्रॉसस्टॉक DSL रिसीवर में प्रमुख हानि होना बंद हो गया है। इसके बजाय, विदेशी शोर स्रोत (संभवतः प्रकृति में रुक-रुक कर) बिजली की आपूर्ति, घरेलू उपकरणों, मोटर्स, वाणिज्यिक रेडियो प्रसारण, और पीएलसी मोडेम जैसे डीएसएल बैंड में अन्य सेवाएं प्राथमिक व्यवसाय बन गई हैं। जबकि इंटरलीव्ड रीड-सोलोमन कोडिंग जैसी तकनीक आधारित त्रुटि सुधार (FEC) और भौतिक परत पुनः प्रवेश, डीएसएल में शामिल मानक इन विदेशी शोर शोर के प्रभाव को कम करने में मदद कर सकते हैं, अतिरिक्त आंशिक या पूर्ण शोर रद्दीकरण FEC और पुनर्संरचना क्षमताओं को पूरक कर सकता है। जबसे तांबे से अधिक डेटा सिग्नल के लिए डीएसएल अंतर मोड (डीएम) ट्रांसमिशन पर निर्भर करता है जोड़े, और विदेशी शोर जोड़े को एक सामान्य मोड के रूप में विद्युत चुम्बकीय रूप से मुड़ जोड़ी पर (सीएम) संकेत, रिसीवर पर एक अतिरिक्त सीएम सेंसर स्वतंत्रता की एक अतिरिक्त डिग्री प्रदान करता है, जिसका उपयोग विभेदक मोड में लीक होने वाले विदेशी शोर को रद्द करने के लिए किया जा सकता है। हालांकि, शोर रद्द करने के लिए सीएम सेंसर का उपयोग करते समय दो मुख्य चुनौतियां हैं। पहली समस्या यह है कि आम मोड से डिफरेंशियल मोड कपलिंग हो सकती है एक रैखिक समय-अपरिवर्तनीय (LTI) प्रणाली के रूप में निर्मित, इसे एक परिमित आवेग के रूप में ग्रहण किया जाना है प्रतिक्रिया (एफआईआर) एक लंबी आवेग प्रतिक्रिया (सैकड़ों नल के आदेश) के साथ फ़िल्टर करती है, और नहीं सरल मॉडल या विस्तृत लक्षण वर्णन उपलब्ध है। इसके परिणामस्वरूप उच्च जटिलता होती है प्रशिक्षण और निरस्तीकरण, साथ ही साथ प्रशिक्षण समय। दूसरी चुनौती यह है कि युग्मन का अनुमान (यानी, शोर कैंसेलर का प्रशिक्षण) उपस्थिति

में किया जाना है विदेशी शोर की तुलना में बहुत मजबूत डेटा मोड सिग्नल (लगभग 25 - 30 डीबी मजबूत) डीएम में संकेत, जो इस समस्या को हानि के प्रकार में दफन ब्याज के संकेत के समान बनाता है आकलन की समस्या। इसलिए, सटीक के लिए बड़ी मात्रा में औसत की आवश्यकता होती है अनुमान, प्रशिक्षण एल्गोरिथ्म के एक धीमी गति से अभिसरण के परिणामस्वरूप। निर्णय-निर्देशित अनुमान सीधे तौर पर नियोजित नहीं किया जा सकता है, क्योंकि डीएम सिग्नल अनियंत्रित विदेशी शोर के लिए शोर के नियमित डेटा मोड सिग्नल की तुलना में अनुपात लगभग 25-30 डीबी तक कम हो सकता है अनुपात (आमतौर पर लगभग 50 डीबी), जिसके परिणामस्वरूप त्रुटि संभावनाएं 1 के करीब हैं। इस थीसिस को हल करना है इन चुनौतियों, ताकि सामान्य-मोड सेंसर का उपयोग करने के लिए व्यावहारिक रूप से व्यवहार्य विधि का निर्माण किया जा सके एलियन नॉइज़ कैंसलेशन के लिए, साथ ही प्रस्तावित विधि पर विचार करके शुरू किए गए अतिरिक्त मुद्दों का पता लगाएं।

हमारा प्रस्तावित समाधान प्रशिक्षण के लिए आवृत्ति-डोमेन “प्रति-स्वर” मॉडल के उपयोग पर आधारित है और रद्दीकरण, जिसमें हम यह मानते हैं कि विदेशी शोर की चक्रीय संरचना है, इस प्रकार सीएम-डीएम सिग्नल कपलिंग मॉडल में एक सन्निकटन शुरू करना। आवृत्ति का उपयोग डोमेन प्रति-टोन मॉडल हमें निर्णय-निर्देशित अनुमान बहुत ही शुरू करने की अनुमति देता है आसानी से DSL OFDM डेटा ट्रांसमिशन का उपयोग करता है। प्रति-टोन मॉडल भी सक्षम बनाता है अन्य कार्यान्वयन से संबंधित होने के अलावा, कम जटिलता प्रशिक्षण और रद्द करना फायदे। हमने प्रशिक्षण के लिए एक कम जटिलता वाले दो-चरण के एल्गोरिदम का प्रस्ताव किया है गैर-निर्णय-निर्देशित पहले चरण के साथ प्रति-टोन कैंसिलर, और दूसरा पुनरावृत्त निर्णय-निर्देशित चरण, जिसमें काफी तेजी से अभिसरण होता है। हमने प्रदान किया है प्रस्तावित एल्गोरिथ्म के दोनों चरणों के अभिसरण का विस्तृत विश्लेषण। प्रस्तावित एल्गोरिथ्म की प्रभावकारिता की

मान्यता एक अतिरिक्त चुनौती प्रस्तुत करती है, क्योंकि विदेशी हस्तक्षेप के लिए कोई मानक सांख्यिकीय शोर मॉडल उपलब्ध नहीं है, इसकी प्रकृति के रूप में स्रोत से स्रोत तक व्यापक रूप से भिन्न होता है। इस समस्या को हल करने के लिए, हमने प्रभावकारिता का प्रदर्शन किया है एक प्रतिकूल गैर-स्थिर शोर मॉडल का उपयोग करके सिमुलेशन के माध्यम से एल्गोरिथ्म।

इसके अलावा, हमने प्रशिक्षण के लिए एक संयुक्त समय और आवृत्ति डोमेन एल्गोरिदम भी प्रस्तावित किया है शोर कैंसेलर, जिसमें उच्च जटिलता है लेकिन बहुत तेजी से अभिसरण और कुछ प्रदान की है इसके अभिसरण के लिए सीमित औचित्य। इसके अतिरिक्त, हमने एक और संस्करण भी प्रस्तावित किया है आवृत्ति-डोमेन प्रति-टोन प्रशिक्षण एल्गोरिथ्म, जिसमें उच्च स्मृति आवश्यकताएं हैं लेकिन दो चरण प्रति टोन एल्गोरिथ्म की तुलना में तेजी से अभिसरण पहले उल्लेख किया गया है। दोनों ये एल्गोरिदम कठोर विश्लेषण के लिए उत्तरदायी नहीं हैं, लेकिन व्यवहार में उपयोगी हो सकते हैं।

थीसिस में अन्य महत्वपूर्ण योगदान पेर-टोन का विश्लेषणात्मक उपचार है आदर्श। पेर-टोन मॉडल, जो यह मानता है कि विदेशी शोर संकेत में सर्कुलर संरचना है, एक अंतर्निहित सन्निकटन है। इस अंतर्निहित सन्निकटन के कारण, पेर-टोन रद्दीकरण में अवशिष्ट रद्दीकरण के बाद का शोर हो सकता है रैखिक (टाइम-डोमेन) कनवल्शन द्वारा रद्द करने में अवशिष्ट शोर से अधिक है। हमने विश्लेषणात्मक रूप से अवशिष्ट शोर शक्ति के लिए अभिव्यक्ति निकाली है और एक "पोस्ट-ट्रेनिंग" देरी समायोजन का उपयोग करके इसे अनुकूलित करने का एक तरीका सुझाया है। इसके बाद, हम युग्मन के "सही" टाइम-डोमेन आवेग प्रतिक्रिया और प्रति-टोन गुणांक के व्युत्क्रम असतत फूरियर रूपांतरण द्वारा प्राप्त प्रतिक्रिया के बीच सटीक संबंध प्राप्त करते हैं। टोलपिट्ज़ और सर्कुलर मैट्रिस के बीच स्पर्शोन्मुख तुल्यता के परिणामों का उपयोग करते हुए,

हम दिखाते हैं कि इस सटीक संबंध को अधिकांश व्यावहारिक मामलों में बहुत सरलता से समझा जा सकता है, जिसके परिणामस्वरूप पेर-टोन गुणांक से समय-डोमेन आवेग प्रतिक्रिया प्राप्त करने का एक सरल तरीका है, जिसमें टर्न का उपयोग बेहतर रद्दीकरण प्रदर्शन की पेशकश के लिए किया जा सकता है। विश्लेषण की इस पंक्ति का उपयोग पेर-टोन मॉडल के अच्छे प्रदर्शन के लिए विश्लेषणात्मक औचित्य प्राप्त करने के लिए किया जाता है, इसके अंतर्निहित सन्निकटन के बावजूद। हम बताते हैं कि पेर-टोन रद्दीकरण के मामले में, अवशिष्ट शोर संभावित रूप से जटिल गैर-परिपत्र रूप से वितरित किया जा सकता है जिसके परिणामस्वरूप प्रदर्शन का कुछ अतिरिक्त नुकसान हो सकता है। हम इस प्रभाव का विश्लेषण करते हैं और बताते हैं कि वाइडबैंड शोर परिदृश्यों के लिए, यह प्रभाव हल्का हो सकता है। इसके अलावा, हम डीएसएल मानकों में उपयोग किए जाने वाले चार-आयामी (4D) ट्रेलिस कोडेड मॉड्यूलेशन (TCM) के प्रदर्शन पर जटिल गैर-परिपत्र रूप से वितरित गौसियन शोर के प्रभाव का विश्लेषण करते हैं, और इस परिदृश्य में कोड के प्रदर्शन को सुधारने के उपाय सुझाते हैं।

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ACRONYMS

ADSL	Asymmetric Digital Subscriber Line
AM	Amplitude Modulation
ARMA	Auto-regressive Moving Average
AWGN	Additive White Gaussian Noise
BER	Bit-Error Rate
CAP	Carrierless Amplitude Phase
CDF	Cumulative Distribution Function
CM	Common Mode
CO	Central Office
CPE	Customer Premises Equipment
CRC	Cyclic Redundancy Check
DD	Decision-Directed
DFT	Discrete Fourier Transform
DMT	Discrete Multi-Tone Modulation
DM	Differential Mode
DSL	Digital Subscriber Line
DSM	Dynamic Spectrum Management
DS	Downstream
EM	Electromagnetic
FDAF	Frequency Domain Adaptive Filtering
FDD	Frequency Division Duplexing
FEC	Forward Error Correction
FEQ	Frequency Domain Equalizer
FEXT	Far-End Cross Talk

FFT	Fast Fourier Transform
FIR	Finite Impulse Response
HDSL	High Speed Digital Subscriber Line
HDTV	High Definition Television
i.i.d.	Independent and Identically Distributed
IN	Impulse Noise
IRC	Interference Rejection Combining
ISDN	Integrated Services Digital Network
ICI	Inter-Carrier Interference
ISI	Inter-Symbol Interference
LMS	Least Mean Square
LS	Least Squares
LSB	Least Significant Bit
LTI	Linear Time-Invariant
MIMO	Multiple-Input Multiple-Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
MU-MIMO	Multi-User MIMO
NAR	Noise Alone Reference
NDBLS	Non Decision-Directed Block Least Squares
NEXT	Near-End Cross Talk
NLMS	Normalized LMS
NM	Noise Margin
OFDM	Orthogonal Frequency Division Multiplexing
PAM	Pulse Amplitude Modulation
PEIN	Prolonged Electrical Impulse Noise
PDF	Probability Distribution Function
PHY	Physical Layer
PLC	Power Line Communications

POTS	Plain Old Telephone System
PSD	Power Spectral Density
PTLB	Per-Tone Lower Bound
QAM	Quadrature Amplitude Modulation
QLN	Quiet Line Noise
REIN	Repetitive Electrical Impulse Noise
RF	Radio Frequency
RLS	Recursive Least Squares
RS	Reed-Solomon
SER	Symbol Error Rate
SHDSL	Symmetric High Bit-Rate Digital Subscriber Line
SHINE	Single High Electrical Impulse Noise
SMPS	Switch Mode Power Supply
SNR	Signal to Noise Ratio
TCM	Trellis Coded Modulation
TDD	Time Division Duplexing
TEM	Transverse Electric Magnetic
TEQ	Time-Domain Equalization
US	Upstream
UTP	Unshielded Twisted Pair
VDSL	Very High Bit-Rate Digital Subscriber Line
xDSL	Umbrella term for all recent DSL standards

NOTATION

Lower-case letters, e.g., y_d , z_d , $\mathbf{h}_{cd}$	Time-Domain Signals
Upper-case letters, e.g., Y_d , $\mathbf{Y}_d$	Frequency-Domain Signals
Boldface letters, e.g., $\mathbf{H}$, $\mathbf{h}_{cd}$	Matrices and Vectors
Superscript with bracket, e.g., $Y^{(n)}$	DMT Symbol Index
Subscript with bracket, e.g., $\beta_{(k)}$	Iteration Index
Subscript d, e.g., Y_d	Differential Mode Signal
Subscript c, e.g., Y_c	Common Mode Signal
Subscript cd, e.g., h_{cd}	Common Mode to Differential Mode Coupling
Subscript dc, e.g., h_{dc}	Differential Mode to Common Mode coupling
Subscript or superscript ndd , e.g., P_e^{ndd}	Non Decision-Directed
Subscript or superscript dd , e.g., β_{dd}	Decision-Directed
Superscript $\dagger$, e.g., $\mathbf{A}^\dagger$	Moore-Penrose Pseudo-Inverse
q	Subcarrier Index
t	Sample Index in Time-Domain
N	Number of DMT symbols
P	Size of DFT in Number of Samples
L	Length of CM to DM Coupling
$\mathbf{h}$, h	Time-Domain Impulse Response
β	Time-Domain Impulse Response
β	Per-Tone Cancellation Coefficient
β	Time-Domain Canceller
$\mathbf{W}_P$	$P \times P$ DFT Matrix (un-normalized)

W_P^{ij}	Twiddle Factor for a P sized DFT
$ _2$	Frobenius Norm
$Q(x)$	Standard Q function defined as $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{x^2}{2}} dx$
$E\{\}$	Expectation Operator
$\mathbf{R}$	Autocorrelation Matrix
$r(i)$	Autocorrelation Sequence
Superscript T , e.g., $\mathbf{h}^T$	Transpose of a Matrix/Vector
Superscript H , e.g., $\mathbf{W}^H$	Hermitian Transpose of a Matrix/Vector
z, Z	Alien Noise Signal
v, V	Background AWGN
x, X	Data Signal
$\Pi_{\text{ slicer}}(Y)$	Slicer or Decision-Device Function, which returns the closest (in terms of squared distance) constellation point to Y